The effect of very low energy solar neutrinos on the MSW mechanism

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We study some implications on standard matter oscillations of solar neutrinos induced by a background of extremely low energy thermal neutrinos trapped inside the Sun by means of coherent refractive interactions. Possible experimental tests are envisaged and current data on solar neutrinos detected at Earth are briefly discussed.

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Experiments detecting neutrinos of energy up to several MeV emitted by the Sun measure particle fluxes [1], [2] which are lower than those predicted by the Standard Solar Model [3], apparently depending on neutrino energy. Recent results obtained by the SNO collaboration [2], regarding charged current as well as neutral current data, have convincingly shown (with a high statistical significance level) that such a deficit is explained in terms of transitions from ν_e into a different (active) flavor state. Furthermore, compelling evidence for atmospheric ν_μ disappearance [4], independently checked by the K2K long-baseline experiment [5], also points towards a natural explanation in terms of neutrino flavor oscillations. However, while atmospheric neutrinos would mainly change flavor during their travel in air (practically, in vacuum), neutrinos emitted by the Sun could experience coherent interactions with the solar matter, enhancing the transition probability according to the MSW theory [6]. As observed, for example, in Ref. [7], the oscillation scenario is nicely confirmed by a global analysis of solar, atmospheric and reactor neutrino experiments, including KamLAND recent results [9]. In particular, possible indications in favor of solar matter effects in neutrino oscillation seem to emerge from a combined analysis of SNO and KamLAND experimental observations [8].

Solar neutrinos detected at Earth are produced deep inside the Sun by the energy generating nuclear fusion reactions, and their (observationally relevant) energy spectrum typically ranges from hundreds of keV to tens of MeV. However, lower energy neutrinos are produced as well in the solar core by means of weak charged and neutral current mediated thermal processes [10]. The mean energy of such neutrinos is of the order of the core temperature ($\sim 1.3\,keV$), so that they account for a negligible fraction of the energy loss ($\sim 0.001\%$) and, therefore, are potentially not relevant for the solar evolution. Nevertheless, as pointed out in Ref. [10], the contribution of solar thermal neutrinos to the flux at earth is dominant in the energy window above the cosmic background energies ($\gtrsim 10^{-2}\,eV$) and below the solar fusion and terrestrial neutrino energy thresholds (around $5\,keV$). Apart from peculiar informations on the Sun properties carried by thermal neutrinos, which would be useful for a further checking of the Standard Solar Model, the detection of the existence of such neutrinos will also translate into stringent kinematic limits on the mass of muon or tau neutrinos. However, despite their importance for Solar and Particle Physics, there is no obvious experiment aimed to give a direct or indirect measurement of thermal neutrinos, due to their low scattering cross section.

In this paper we will focus on extremely low energy neutrinos and discuss an intriguing possibility for an indirect test of solar thermal neutrinos, assuming that the higher energy ones (from nuclear fusion reactions) experience flavor oscillations in the Sun, according to the MSW theory.

NEUTRINOS TRAPPED IN THE SUN

It is commonly believed that, due to their extremely small cross section, very low energy neutrinos produced in a star freely escape from it. This reasoning does not take into account, however, coherent interactions with the particles in the plasma which, as shown by Loeb [11], become important at low energy. In practice the refractive index of neutrinos with energy E in matter, of order $G_F N/E$ (G_F is the Fermi coupling constant and N is the number density of particles in the plasma interacting with neutrinos), approaches unity at very low energies, so that a complete inner reflection takes place. As a consequence trapped neutrinos exist inside the Sun (and, in general, in every star). Smirnov and Vissani [12] have pointed out the crucial role played by such neutrino sea in order to solve the problem of an unphysically large value for the self-energy of stars due to many-body long-range neutrino forces.

The weak interaction of thermal neutrinos with the particle in the solar medium can be parameterized in terms of an effective potential [13]

$$V_{\nu_e} = \pm\sqrt{2}\,G_F\left(N_e - \frac{1}{2}N_n\right) \qquad (1)$$

for ν_e and

$$V_{\nu_x} = \mp\frac{G_F}{\sqrt{2}}N_n \qquad (2)$$

for non-electron neutrinos ($x = \mu, \tau$). Here N_e and N_n are the electron and neutron number density of the plasma, respectively; the upper sign refer to neutrinos, while the lower one to antineutrinos. Effectively, the star can be viewed as a potential well for neutrinos with depth given in Eq. (1) or (2). Since, in the Sun, we typically have $N_e > N_n/2$, ν_e and $\overline{\nu}_x$ experience a repulsive potential, while an attractive one acts on $\overline{\nu}_e$ and ν_x. As a result the Sun expels ν_e, $\overline{\nu}_\mu$ and $\overline{\nu}_\tau$, while non-electron neutrinos and electron antineutrinos are trapped inside it.

MODIFIED MSW EFFECT

For massive neutrinos, flavor eigenstates created by weak interactions are, in general, linear superposition of the propagating mass eigenstates, and the phenomenon of flavor oscillations can take place [14]. Assuming, for simplicity, transitions between only two (active) flavor states ν_e and ν_a ($a = \mu, \tau$), the evolution equation for solar neutrinos reads as follows [15]:

$$i\frac{d}{dx}\begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} = H \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} , \qquad (3)$$

where the Hamiltonian matrix can be cast in the form

$$H = H_0 + H_{\text{int}} \qquad (4)$$

with

$$H_0 = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} , \qquad (5)$$

$$H_{\text{int}} = \frac{1}{2}\begin{pmatrix} V & 0 \\ 0 & -V \end{pmatrix} . \qquad (6)$$

Here E is the neutrino energy, $\Delta m^2 = m_2^2 - m_1^2$ is the squared mass difference between the two mass eigenstates and θ is the (vacuum) mixing angle. The potential V (depending, in general, on the position x) is given by the difference between the ν_e and ν_a interaction energies with the solar matter:

$$V = V_{\nu_e} - V_{\nu_a} . \qquad (7)$$

In the ordinary MSW theory, assuming the (neutral) medium to be composed of electrons, neutrons and protons, the potential in Eq. (7) depends only on the electron number density N_e [6], [13]:

$$V = \sqrt{2}\, G_F N_e . \qquad (8)$$

However, as seen above, a sea of thermal neutrinos and/or antineutrinos exists in the Sun which, in principle, influences the propagation of fusion neutrinos escaping from the star and detected at Earth. The interaction energies of ν_e and ν_a propagating in a medium composed also of thermal neutrinos with number densities N_i ($i = \nu_e, \nu_\mu, \nu_\tau, \overline{\nu}_e, \overline{\nu}_\mu, \overline{\nu}_\tau$) has been calculated in Ref. [13] [18]

$$V_{\nu_e} = \sqrt{2}\, G_F \left\{ N_e - \frac{1}{2}N_n + 2\left(N_{\nu_e} - N_{\overline{\nu}_e}\right) + \right.$$
$$\left. \left(N_{\nu_x} - N_{\overline{\nu}_x}\right)\right\} \qquad (9)$$

$$V_{\nu_a} = \sqrt{2}\, G_F \left\{ -\frac{1}{2}N_n + \left(N_{\nu_e} - N_{\overline{\nu}_e}\right) + \right.$$
$$\left. 2\left(N_{\nu_x} - N_{\overline{\nu}_x}\right)\right\} . \qquad (10)$$

As pointed out above, the solar plasma acts through a repulsive potential on thermal ν_e and $\overline{\nu}_x$, so that for simplicity we definitively assume that $N_{\nu_e} = N_{\overline{\nu}_x} = 0$ in the Sun. The difference in Eq. (7) then takes the form:

$$V = \sqrt{2}\, G_F\, \alpha\, N_e \qquad (11)$$

with

$$\alpha = 1 - \frac{N_{\overline{\nu}_e} + N_{\nu_x}}{N_e} . \qquad (12)$$

The effect of the thermal neutrino sea on the MSW mechanism is thus simply parameterized in terms of the quantity α in Eq. (12): for $\alpha = 1$ we recover the ordinary MSW theory. Note that since the trapping of thermal $\overline{\nu}_e$ and ν_x is ruled by coherent interactions with the electrons (and neutrons) in the plasma (see Eqs. (1) and (2)), it is natural to expect that, at a rough approximation, the parameter α is nearly constant through the Sun. In this case the structure of the evolution equation in (3) does not change (no x-dependent term appears) and the oscillation probability changes only for a multiplicative constant factor in V.

THEORETICAL PREDICTIONS FOR THE NEUTRINO SEA

Very low energy neutrinos are created in stars by a number of electroweak processes. Usually one can think about URCA processes, neutrino pair bremsstrahlung or even production induced by many-body long-range forces [12]. To our best knowledge, the most complete study present in the literature regarding the production od sub-keV neutrinos has been performed in Ref. [10]. Here the authors show that the relevant processes in the Sun are: 1) Compton production; 2) intermediate plasmon pole contribution to the Compton process; 3) transverse plasmon decay into neutrino-antineutrino pairs; 4) decay of thermally populated excited nuclear states into neutrino-antineutrino pairs by means of Z^0 emission; 5) pair production in electron transitions from free to bound atomic states. It is found that the pole contribution to

the Compton process dominates the production of low energy ($< 5\,keV$) ν_e and $\overline{\nu}_e$ while, for non-electron neutrinos, the dominant channel below $2\,keV$ is the free-bound process.

Let us now assume, as above, that extremely low energy $\overline{\nu}_e, \nu_\mu, \nu_\tau$ are completely trapped inside the Sun. A rough estimate of the number densities of such neutrinos, relevant for the evaluation of the parameter α in Eq. (12), has been previously given in [12]. Assuming thermodynamical equilibrium and strong fermion degeneration for the neutrino sea, the number density of the particles in the bath is $N_\nu \sim \mu^3 \sim V^3$, where μ is the neutrino chemical potential which would be of the same order of magnitude of the potential in Eq. (1) or (2). In this case the resulting N_ν is exceedingly small, of the order of $10^{-28}\,cm^{-3}$. However, in this estimate it has not been taken into account that the production reactions (for example those considered in [10]) render neutrino trapping a *non-equilibrium* phenomenon. Then it seems natural to assume that the number densities of trapped very low energy neutrinos is much greater than the corresponding equilibrium values [19], as for example happens in the early Universe plasma during primordial nucleosynthesis [16]. Therefore, since the Standard Solar Model in its present form explains well the observed properties of the Sun [3], we have only to ask that the energy density of trapped neutrinos is much lower than the energy density of the solar plasma of electrons, protons and neutrons. in order to not affect solar dynamics. To obtain a rough limit on N_ν, let us assume for simplicity that the energy density ρ of the solar plasma is contributed only by electrons at a temperature of order $1\,keV$: $\rho_e \sim N_e \cdot < E_e > \sim N_e \cdot T \sim 10^{14} eV^4$. By taking the typical energy of trapped neutrinos to be of the order of the potential in Eq. (1) or (2) (as also assumed in [11] and [12]), and requiring that the energy density of the neutrino sea $\rho_\nu \sim N_\nu \cdot E_\nu$ is much lower than ρ_e, we get the very weak limit $N_\nu \ll 10^{41}\,cm^{-3}$. In practice, using the above arguments, even if the number density ratio in Eq. (12) approaches the face value 1, the energy density of trapped neutrinos would account for only $10^{-2}\,eV^4$ (i.e. about 14 orders of magnitude less than electrons), and solar evolution is completely unaffected.

EXPERIMENTAL TESTS

The indirect detection of the neutrino sea in the Sun can be carried out by studying solar neutrino oscillations and measuring the parameter α in Eq. (11). The effect considered here depends, of course, on the number density of the particles in the sea, and any observed deviation from the standard MSW prediction ($\alpha = 1$) in the direction underlying Eq. (11) ($\alpha < 1$) should be ascribed to the presence of a neutrino sea in the Sun.

The feasibility of such kind of analysis, in the near future, is well outlined in a recent paper by Fogli et al. [8]. Here the authors perform global fits of current solar neutrino data together with CHOOZ reactor observations [17] and recent KamLAND results [9], obtaining indications in favor of neutrino matter oscillations in the Sun. This is achieved by means of a χ^2-analysis for the parameter α actually appearing in our Eq. (11): a value $\alpha = 0$ would indicate no matter effects (vacuum oscillations), while $\alpha = 1$ is an evidence for the (standard) MSW theory. However, in the light of the mechanism proposed here, observed values for α different from 1 would give strong evidence in favor of the existence of the solar neutrino sea.

As a result, with current data, the authors of Ref. [8] find a best fit value for α close to unity (slightly greater than 1) with an overall $\pm 3\sigma$ range spanning about three orders of magnitude (approximately $10^{-1} \lesssim \alpha \lesssim 10^2$). While this allowed range is rather large, and no firm conclusion can be reached neither on general matter effects in solar neutrino oscillations nor on the presence of effects induced by a neutrino sea, nevertheless it is interesting to observe that simulated data for the KamLAND experiment with increased (a factor 10) statistics would exclude values for α greater than 1 *but not* those corresponding to $\alpha < 1$. Since a value for α *lower* than unity is a peculiar prediction of the mechanism considered here (see Eq. (12)), if such a poor indication will be confirmed by future experiments, it would give a strong evidence for the sea of very low energy neutrinos in the Sun.

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[18] Since ν_μ and ν_τ (and their antiparticles) contribute in the same way to the potential energies through neutral current interactions only, for simplicity we set $N_{\nu_x} = N_{\nu_\mu} + N_{\nu_\tau}$ and similarly for antineutrinos.

[19] Note that if the sea is far from thermodynamical equilibrium, the Pauli blocking mechanism could not give a stringent limit on the number of neutrinos in the bath. In fact the Pauli principle forbids the filling of one-particle states with more than one neutrino, but the distribution with energy of these states is not related to the Fermi distribution for non-equilibrium configurations. In principle we can then think to peculiar distributions with many states at very low energies and few states at higher energies, where neutrinos are no longer trapped by refraction.